3

Eutrophication of Lakes

By W. D. Williams

Department of Zoology, Monash University, Clayton, Victoria 3168
Victoria 3168

Introduction

At a Symposium such as this, specifically organized to promote information exchange between personnel in different fields, and with published Proceedings, speakers are on the horns of a dilemma. On the one side, there is the actual business of getting across in comprehensible terms the speaker's viewpoint to a general audience—here the viewpoint of an academic limnologist; and on the other, there should be the desire to prevent needless repetition in the literature of known material. One solution is two lectures: one spoken and one written. This, however, partly discredits the Proceedings as the published events of the Symposium.

I take the road of partial compromise. I propose to explain some basic concepts relating to eutrophication, to examine some causes and effects of what we are pleased to call cultural eutrophication, although there is little that is cultural about the process in the usual sense of that word, and to discuss preventive and remedial practices. I will conclude by briefly discussing an Australian example. In the written account there is an extensive bibliography that will serve to introduce non-biologists to pertinent literature, with particular regard to preventive and remedial measures.

It is pertinent to begin my address by briefly defining eutrophication. In the present context, I refer to the increase in lake productivity, brought about by the addition of plant nutrients resulting from human activities on the lake catchment area.

May I further preface my address by saying that recently I attended the International Symposium on Eutrophication, held in Madison, Wisconsin (for comments on this, see Williams 1968a). At Madison, 250 participants were expected, and 600 arrived. This, I believe, indicates the seriousness with which eutrophication is now viewed in the United States and elsewhere. A symposium such as the present one which includes an account of eutrophication is therefore hardly premature for Australia. Perhaps we have here the first indication that man's evolving recognition of his ultimate responsibility for the state of this planet must not always be based upon hindsight.

Basic Concepts

Almost all energy for life on earth is derived from the sun's radiant energy; the small amount of chemical energy that some autotrophic organisms use is negligible in comparison. Huge amounts of solar energy reach this planet: an approximate figure of $15{\cdot}3 \times 10^8$ cal m^{-2} year^{-1} is quoted by Phillipson (1966). Not all of this, however, is available for use, and ultimately only about 5 to less than 1 per cent is converted into chemical energy by the process of photosynthesis. The huge difference is used in evaporating water, scattered by atmospheric dust particles, or, as happens to most, otherwise lost (made unavailable) by conversion into heat or by reflection.

The efficiency of fixation, the autotrophs involved, and the ecological pathways subsequently taken by the fixed energy vary according to the nature of the environment receiving the solar energy. In lakes, three principal autotrophic components may be delimited: phytoplankton, periphyton, and macrophytes. The extent to which each contributes to the total sum of solar energy fixed is largely a function of lake morphometry (at least in freshwater lakes). In general, the smaller the lake, the greater the contribution from periphyton and macrophytic vegetation; conversely, in very large lakes almost all solar energy is fixed by phytoplankton.

Part of the fixed energy is used by the autotrophs for metabolic maintenance (about 20 per cent), but there is a surplus used for growth, and it is this that supports heterotrophic organisms. The rate of chemical energy synthesis, or in other words the amount of carbon fixed per unit time, per unit area or volume, is referred to as the gross primary productivity; the amount actually available for heterotrophic nutrition is the net primary productivity.

Values for primary productivity vary from lake to lake, and of course according to the plants involved. Two extreme values are those of Goldman, Mason and Hobbie (1967) and of Steemann Nielsen (1955). The former studied a saline lake in Antarctica and recorded a photosynthetic rate of carbon fixation of only 14 mg C m^{-2} day^{-1} in February (summer). Steemann Nielsen, on the other hand, found that the annual mean value in Sollerod Sϕ, a Danish freshwater lake receiving large amounts of purified sewage, was 1,430 mg C m^{-2} day^{-1}. Both these values were based only upon phytoplankton determinations, but as is especially shown by the work of Wetzel (1963, 1964) important contributions may also be made by periphyton and macrophytes even in comparatively larger lakes.

Lakes with low primary productivities are in general said to be oligotrophic, those with high ones, eutrophic. An intermediate category, mesotrophic, is also defined. Other distinguishing criteria exist but need not be discussed.

Because lakes generally act as nutrient traps as well as settling basins, the three categories often form an evolutionary sequence, from oligotrophic through mesotrophic to eutrophic. Eutrophic lakes in turn give rise ultimately to marshlands and then *terra firma* as the result of the accumulation of organic and inorganic material derived from geological and biological processes. It is because of this sequence that all but the deepest lakes are rather ephemeral ecosystems when measured in meaningful time units for evolution.

Eutrophication, or the gradual conversion of oligotrophic and mesotrophic lakes to eutrophic ones, is therefore essentially a natural phenomenon. As such it is usually a slow process when measured in human life-spans, and ordinarily causes no concern. That it does is due to the tremendous acceleration brought about by certain human activities; it is this accelerated process that is referred to as cultural eutrophication.

Causes of Cultural Eutrophication

Although eutrophication is the result of an increase in the lake of nutrient materials, over any short time interval in a lake not subject to human influence there is a balance, more or less, between nutrient inflow and nutrient outflow and decay. The presence of man, and especially urban man, greatly alters this balance in most cases. Thus, the addition to the lake of unnaturally large amounts of nutrients in the form of untreated or treated sewage effluents, fertilizers, certain sorts of detergents, storm water and so on quickly becomes an established feature of man's occupancy of lakeside regions. Particularly important amongst these nutrients are certain compounds which in nature are present in limiting amounts, and especially implicated are nitrates and phosphates. Indeed, many remedial or preventive efforts centre around the removal of these anions from effluents, as I shall point out later. Other nutrients are implicated, but not to the same extent. Thus, in Australia in particular, but also elsewhere in general, some eutrophication may result from the mere increase in total dissolved solid content of inflows: several North American authors have shown rough correlations between T.D.S. concentrations and productivity (Northcote and Larkin 1955, Kerekes and Nursall 1966), and it is known that grazing, land-clearing, and other human activities which alter the natural pattern of run-off frequently cause increased stream salinities (e.g. Wood 1924).

The effect of artificial addition of agricultural fertilizers to oligotrophic lakes is often instructive. A noteworthy Australian experiment of this sort was performed by Weatherley and Nicholls (1955) who added a mixture of superphosphate, ammonium sulphate, potassium chloride and ground limestone to Lake Dobson, an oligotrophic highland lake in Tasmania. Following the addition, a prolific increase in macrophytic growth was one observed effect.

Basically, we may conclude, cultural eutrophication is caused by man's indifference to the natural environment, and by the (unjustified) assumption that the homeostasis of the biosphere will always compensate for human alteration to it.

Effects of Cultural Eutrophication

For most purposes, oligotrophic lakes are the most appealing to man. Standing crops of biota are low with high biotic diversity, water blooms (very high algal concentrations over a given period of time) are absent or rare, water transparency is high, nutrients and dissolved solids are present in low concentrations, and oxygen occurs in the hypolimnion throughout the year. Oligotrophic lakes are frequently characterized by salmonid fishes (either indigenous or introduced), and amongst the algae by certain species of *Staurastrum, Tabellaria, Cyclotella* and *Dinobryon*. From the engineering viewpoint, water from these lakes is of high quality, and in choice of location, erection and subsequent maintenance of reservoirs efforts are made to reproduce and maintain oligotrophy (Pearsall, Gardiner and Greenshields 1946).

Eutrophic lakes, on the other hand, are characterized by high standing crops of biota, low biotic diversity and transparency, frequent water blooms, and high nutrient content. Oxygen is often completely absent from the hypolimnion during the summer resulting in additional release of nutrients previously bound at the mud/water interface under aerobic conditions. Oxygen depletion also results in the absence of salmonids. Algae characteristically belong to the Cyanophyceae, e.g. *Anabaena, Aphanizomenon, Microcystis, Oscillatoria*, or are genera different from those present in oligotrophic lakes, e.g. *Asterionella, Stephanodiscus, Fragilaria, Melosira*. (It should be emphasized, however, that great care is needed in the use of algae as indicators of eutrophy or oligotrophy.)

These and other characteristics of eutrophic lakes are frequently more pronounced when eutrophication is cultural. Indeed the question has been raised as to whether the extreme conditions in some culturally eutrophicated lakes have any exact natural parallel.

Bearing in mind the overall aims of this symposium, it is worthwhile to consider in more detail how the eutrophication of aquatic environments impinges upon their use by man.

The production of excessive amounts of algae may have a number of effects.

In waters used for industrial or municipal purposes, algal overproduction may result in rapid clogging of filters even after usual prefiltration techniques of coagulation and sedimentation. Algal blooms often result in aesthetically unpleasant slimy floating masses of algae which may litter beaches when blown shorewards, and which on decay produce objectionable odours (decaying *Cladophora* smells like a pig-sty). Floating algal masses on decay may cause fish kills as the result of oxygen depletion, and oxygen depletion will certainly cause the replacement of salmonids by other fish, a replacement generally not pleasing to the anglers. Large amounts of certain blue-green algae in particular impart unpleasant tastes and odours to lake waters, and a number of cases are known in which toxic substances liberated by cyanophyceaens brought about fish mortalities and the death of pastoral stock. An early Australian case is noted by Francis (1878). Large standing crops of phytoplankton also, of course, impair light penetration and give rise to murky waters, or at least waters far removed from 'clean blue lake waters' mentally associated with aesthetically pleasing inland lentic waters.

The extensive growths of submerged or emergent macrophytes characteristic of highly eutrophic lakes are of nuisance value when they hinder boating, swimming, fishing, water-skiing or other recreational activities associated with water. Furthermore, macrophytes play a major role in the extinction of lake basins, and there is some evidence that submerged macrophytes promote infections of 'bather's itch' in that a suitable environment is provided for intermediate snail hosts. The mere physical effect of the presence of macrophytes may also provide a suitable environment for such nuisance insects as mosquitoes.

It is unnecessary to discuss the numerous examples of culturally eutrophicated lakes to illustrate some or all of these effects. Nevertheless, the aims of this Symposium suggest that a brief and documented survey of eutrophicated lakes—albeit selective—may not entirely be out of place. Hasler (1947) provides a comprehensive source of examples up to 1947.

An unusual and interesting example of cultural eutrophication during Roman antiquity is recorded by Cowgill and Hutchinson (1964). Sediment cores from Lago di Monterosi indicated a rapid change from oligotrophy to eutrophy during the third century B.C. and this change may be correlated with increased inflow of nutrients following the construction of the Via Cassia.

Nearer the present, mention may be made of Zürichsee in Switzerland. Incipient eutrophication began about 1896 and was characterized by a bloom of *Tabellaria fenestrata* (Lyngbye) Kützing, hypolimnetic oxygen depletion, the disappearance of the profundal fauna, and the occurrence of winter blooms of *Oscillatoria rubescens* de Candolle (Hasler 1947, Ruttner 1963). Eutrophication continues and Thomas (1965) describes how a further nuisance alga, *Hydrodictyon reticulatum* (L.) Lagerheim appeared in considerable quantities for the first time in 1961.

Tabellaria fenestrata has also appeared in Lake Windermere in the English Lake District together with *Asterionella* and various blue-green algae such as *Anabaena* and *Coelosphaerium*. Prior to about 1910, when the great lakeland influx of visitors and new residents began, blue-green algae were rare (Annual Reports of the Freshwater Biological Association 1937-46, Pennington 1943, Hasler 1947).

In North America, perhaps the most discussed examples are the series of four lakes at Madison, Wisconsin: Lakes Mendota, Monona, Waubesa and Kegonsa (e.g. Sawyer 1947, Mackenthun and Ingram 1964). Originally the Madison sewage plant effluent was discharged into Lake Waubesa, and this lake not surprisingly developed heavy algal blooms. Investigation showed that 75 per cent of total inorganic nitrogen and 88 per cent of total inorganic phosphorus entering Lake Waubesa came from the sewage effluent. Nowadays this is diverted by conduit around the lakes (Frey 1963).

Lake Zoar, Connecticut (Benoit and Curry 1961), Lake Tahoe, Nevada/California (Ludwig, Kuzmier, Czak and Carter 1964), and Klamath Lake, Oregon (Phinney and Peck 1961) are further North American examples. The largest examples of interest are undoubtedly Lakes Erie and Ontario, the eutrophication of which has been discussed by Beeton (1961, 1965) and Davis (1964). The depletion of oxygen in Lake Erie was discussed recently by Carr (1962) who noted that at present 'hundreds of square miles of the bottom waters have no detectable oxygen during part of the year', a condition which appears to have become more prevalent over the past thirty years.

In an age of wholesale unconcern towards conservation of the natural environment, immense political inertia, and multiplicity of involved interests, a most promising example of what can be done to combat cultural eutrophication is presented by Lake Washington, Seattle (Edmondson, Anderson and Peterson 1956, Anderson 1961, Edmondson 1966). Since 1946 the human population around this lake has increased rapidly, and as a result increasingly larger volumes of sewage effluent have been added to the lake waters. In 1955, a bloom of *Oscillatoria rubescens* was recorded, a notorious indicator of eutrophication, while over the period 1933-1965 there has been a gradual decrease in transparency with increases in algal numbers and phosphate and nitrate concentrations. Following extensive political manoeuverings (a readable account is given by Clark 1967), a large sewage diversion scheme was begun about 1961. It is not yet quite finished, but already there are indications that at least the rate of eutrophication has decreased and even that there have been 'improvements' (e.g. increased transparency) in certain characteristics.

Preventive and Remedial Measures

It is appropriate here to begin by briefly outlining some parameters used to determine degree of eutrophication. Some qualitative indications have already been mentioned with respect to algae and because of the cosmopolitanism of freshwater algal species (Lund 1965) these may be applicable in Australia. Faunal changes may also provide useful qualitative indications, but their use in Australia is difficult since the fauna is so highly endemic (Williams 1968b). Quantitative biological parameters include determinations of primary productivity, standing crops, phytoplankton pigment concentrations, and relative proportions of given species. Quantitative physical-chemical parameters are sediment core analyses, and determination of hypolimnetic oxygen deficits, transparency, dissolved solid content and concentrations of particular nutrients especially phosphates and nitrates. It should be emphasized, however, that no single parameter provides an absolute yardstick: rather it is a combination of measurements compared between lakes that allows meaningful conclusions.

Knowledge of basic concepts leads easily to the most obvious and fundamental preventive measure: all nutrient material should be denied access. Unfortunately, it is not always possible to do this, but one way around the difficulty is to remove from effluents the two nutrients most implicated in eutrophication, nitrates and phosphates. Chemical engineers have provided methods for this; thus phosphates can be almost eliminated using aluminium sulphate (Lea, Rohlich and Katz 1954, Curry and Wilson 1955, Malhotra, Lee and Rohlich 1964), ferric chloride and sulphate (Thomas 1955), alum and activated silica (Neil 1957), lime (Owen 1953) or other coagulants. Nitrates are less easily removed chemically, but McGauhey, Eliassen, Rohlich, Ludwig and Pearson (1963) report on a method developed by Nesselson involving ion exchangers. Other methods of nutrient removal include pre-blooming in artificial ponds, and in special cases complete distillation. Where nutrient removal is not attempted, the effect of effluents upon the lake can sometimes be mitigated by their discharge near the lake outflow.

Knowledge of basic concepts also suggests a number of internal remedial measures once eutrophy has arrived. Thus, intensive removal of fish, algae or macrophytes effectively decreases the total nutrient content and may be expected to cause decreased eutrophication rates and some improvement in nuisance conditions. In stratified lakes removal of hypolimnetic water rich in nutrients during the summer stagnation period is also a recommended procedure. It is necessary to add, however, that once eutrophication has occurred man may never be able to reverse the process.

Many current remedial measures for alleviation of nuisance characteristics are far less fundamental in character. Principally these are of a mechanical or chemical nature. Mechanical control with cutters largely applies to rooted macrophytes, whereas chemical control using a wide variety of organic and inorganic poisons applies to macrophytes, phytoplankton and various nuisance animals. In the past, chemicals chiefly used were inorganic, mainly copper sulphate for algal control and sodium arsenite for submerged macrophyte control, but now organic poisons are perhaps more frequently involved. With both sorts the attendant long-term changes to the aquatic fauna as well as to man cannot be emphasized too strongly, and it should also be emphasized that poisoning can be only a short term measure.

Cultural Eutrophication of Lake Wendouree, Ballarat

The problem of cultural eutrophication is not yet ordinarily of great moment in Australian lakes, although this picture may be expected to change in the future (Williams 1967). Largely this favourable situation results from the unique distribution of the Australian population; most Australians live near the coast and consequently urban and industrial effluents are discharged directly into the sea (where, however, localized marine eutrophication may be a danger, *vide* Gilmour 1965, Higginson 1966). However, cultural eutrophication is occurring in several Australian freshwater lakes and Lake Wendouree at Ballarat, Victoria, appears to be one of them.

Lake Wendouree (Pl. 1) is a small, shallow, artificial lake constructed late last century upon the site of a natural marsh. Its area is slightly less than 250 ha, its average depth is about 1 m, and its maximum depth when the lake is full is rather less than 2 m. In May 1968 total phosphates were 0·186 mg/l, orthophosphate was 0·176 mg/l, and nitrate concentration was 0·504 mg/l (S. U. Hussainy, personal communication). The lake lies within the township of Ballarat and is approximately two-thirds encircled by urban buildings and one-third by parkland (the Botanic Gardens, and a golf course). It is used extensively by local residents for sailing, rowing, swimming, and fishing. Unfortunately, all of these activities are nowadays more and more hampered by extensive growths of submerged and emergent macrophytes. The principal noxious submerged weed is *Myriophyllum elatinoides* Gaud., but also present are *Vallisneria spiralis* L., *Potamogeton ochreatus* Raoul, *P. pectinatus* L. and *P. tricarinatus* F. Muell. and A. Bennett. Control of these and emergent macrophytes (mainly *Eleocharis spacelata* R. Br.) has hitherto been by mechanical cutting, the total cost of this having risen gradually from about $600 p.a. in 1944-45 to about $10,000 p.a. in recent years.

Unfortunately, this annual harvesting of nutrients has not been as effective as it might have been. Some of the reasons for this appear clearly to be due to the inefficient methods of weed removal. Thus cut weed was left floating freely in the water until it drifted to the shore whereupon it was removed and stacked along the bank for a variable period of time until finally removed altogether from the lake site. Part of the cut weed, however, sank before it reached the shore and therefore contributed to the further enrichment of the lake; in this connection, it is noteworthy that in related species of *Myriophyllum* (*M. spicatum* L.) vegetative propagation from small parts of whole plants appears to be more significant for dispersal and abundance than sexual reproduction (Patten 1956). Once removed from the lake the weeds were often left decomposing upon the shore for a considerable time before final removal. This procrastination resulted, in effect, in the creation of large compost heaps running parallel to the shoreline. The nutrients from these no doubt quickly leached into the lake.

In 1964 I was approached by Ballaarat City Council who requested advice. Following a short visit to the lake I made the following suggestions and it is perhaps not without interest if they are reiterated here:

1. Bank erosion should be guarded against.
2. Siltation ponds should be erected on inflows to prevent further entry of silt.
3. No sewage or organic matter should be allowed to enter the lake. Involved here is material in effluents from the neighbourhood of the Botanic Gardens, in run-off from the golf course, and in any septic effluents from the urban development.
4. As much weed as possible should be removed from the lake at every opportunity. In particular, during cutting operations all practicable attempts should be made to remove as much of the weed from the water as soon as possible after cutting. This might most conveniently be effected by equipping the cutters with a half-emergent rake.
5. All cut weed should be removed immediately from the lake site, including existing dumps.
6. Decaying vegetable matter deposited on the lake bottom should be dredged and removed from the lake site.
7. Fringing trees which are deciduous and deposit leaves in the water should be cut down or suitably pruned. It is clear that a considerable accession of organic material to the lake results from this source (many oaks, elms and other deciduous trees occur around the lake and in adjacent urban and parkland areas).
8. Those areas in the lake where continual weed-dumping has resulted in the creation of a peat-like deposit rich in humus should be excavated and filled with sand or stones.

Measures such as these will not rapidly alter the character of the lake. Nevertheless, I believe that over a period of years they would result in some rejuvenation, although some seasonal weed-cutting will probably always be necessary.

There are two other possible ways by which the weeds in Lake Wendouree may be controlled. These are by the introduction of weed-eating animals, and by poisons (Speirs 1948).

Some animals which it is said could control the weeds by their feeding habits are the manatee (*Trichechus* sp.), a mammal, and certain species of *Tilapia* and *Ctenopharyngodon* (fish). Manatees, however, are rare animals, and the three species are confined to the Americas or western Africa (the Australian relative, *Dugong dugon*, is a marine form confined to tropical waters and therefore unsuitable). *Tilapia* and *Ctenopharyngodon* are forbidden imports in Australia.

As a biologist with grave reservations concerning the long-term effect of insecticides, weedicides, algicides and other poisons upon the natural environment (*vide*, e.g. Rudd 1964, Dunbavin Butcher 1965), it is with considerable hesitation that I discuss control by poison. At best, poisoning can provide only a relatively short term solution. The best known poison for macrophytic control is sodium arsenite. However, the introduction of arsenic compounds into a lake subject to such multipurpose use seems inadvisable. Many organic herbicides are now commercially available, and some of these are extremely effective; 'aqualin' for example, has almost completely cleared Albert Park Lake, Melbourne, of weeds. This chemical is also widely used by the State Rivers and Water Supply Commission to clear their irrigation canals of weed growth. It is, however, expensive, dangerous, apparently needs to be administered fairly regularly to maintain control, and is extremely lethal to fish, as indicated by the virtual absence of fish in Albert Park Lake, and by Jones (1964) who showed that 'acrolein' (apparently an alternative trade name for 'aqualin') is lethal to certain fish at concentrations as low as 0·08 ppm. A figure of $40,000 has been mentioned as the cost of poisoning Lake Wendouree with 'aqualin'.

Those herbicides that are claimed to be effective against aquatic weeds but non-toxic to fish include 'diquat', 'paraquat', and '2, 4-D' (aqua-kleen 20). Like 'aqualin' they are expensive and need to be administered fairly regularly. The use of '2, 4-D' might be appropriate in Lake Wendouree because the area from which it is desired to eliminate weeds can be more or less defined. The central stands of emergent rushes needed to protect boathouses could therefore be left *in situ*.

The toxicity of numerous herbicides to fish are tabulated by Jones (1964), and Dunk (1954, 1955, 1957) has given details of the various experiments that the Victorian State Rivers and Water Supply Commission has undertaken with selected herbicides.

Acknowledgements

I thank Mr S. U. Hussainy, Monash University, for determinations of nitrates and phosphates in Lake Wendouree, and Dr Hilary Jolly, MWS & D Board, Sydney, for commenting on the draft manuscript.

References

(Apart from text references, some others are listed that are likely to be of interest or use to those involved in problems related to cultural eutrophication.)

* Alabaster, J. S., 1960. Toxicity of weed-killers, algicides and fungicides to trout. *Proc. Br. Weed Control Conf.* 4: 1-2.

† Anderson, G. C., 1961. Recent changes in the trophic nature of Lake Washington. In: *Algae and Metropolitan Wastes*. Cincinnati: Robert A. Taft Sanitary Engineering Center.

Beeton, A. M., 1961. Environmental changes in Lake Erie. *Trans. Am. Fish. Soc.* 90: 153-9.

————, 1965. Eutrophication of the St. Lawrence Great Lakes. *Limnol. Oceanogr.* 10: 240-54.

Bennett, G. W., 1962. *Management of Artificial Lakes and Ponds*. New York: Reinhold.

† Benoit, R. J. & Curry, J. J., 1961. Algae blooms in Lake Zoar, Connecticut. In: *Algae and Metropolitan Wastes*. Cincinnati: Robert A. Taft Sanitary Engineering Center.

Butcher, A. Dunbavin, 1965. Wildlife hazards from the use of pesticides. *Australas. J. Pharm.* November: S105-9.

Carr, J. F., 1962. Dissolved oxygen in Lake Erie, past and present. *Publs. gt. Lakes Res. Div.* 9: 1-14.

Chancellor, A. P., 1948. *The Control of Aquatic Weeds and Algae*. London: H.M.S.O.

Clark, E., 1967. How Seattle is beating water pollution. *Harper's Magazine*, June: 91-5.

Cowgill, U. & Hutchinson, G. E., 1964. Cultural eutrophication in Lago di Monterosi during Roman antiquity. *Verh. int. Verein. theor. angew. Limnol.* 15: 644-5.

† Curry, J. J. & Wilson, S. L., 1955. Effects of sewage-borne phosphorus on algae. *Sewage ind. Wastes*, 27: 1262-6.

Davis, C. C., 1964. Evidence for the eutrophication of Lake Erie from phytoplankton records. *Limnol. Oceangr.* 9: 275-83.

Dunk, W. P., 1954. Weed control in irrigation channels and drains. *Tech. Bull. St. Rivers Wat. Supply Comm. Vict.* 8.

———, 1955. Weed control in irrigation channels and drains. *Ibid.* Supplement to 8.

———, 1957. Weedicides. Their properties and application for the control of water-weeds. *Aqua, Melb.* 9 (1): 3-9.

Edmondson, W. T., 1966. Changes in the oxygen deficit of Lake Washington. *Verh. int. Verein. theor. angew. Limnol.* 16: 153-8.

———, Anderson, G. C. & Peterson, D. R., 1956. Artificial eutrophication of Lake Washington. *Limnol. Oceanogr.* 1: 47-53.

Francis, G., 1878. Poisonous Australian lake. *Nature*, 18: 11-12.

Frey, D. G., 1963. Wisconsin: the Birge-Juday era. In: D. G. Frey (Ed.), *Limnology in North America*. Madison: University of Wisconsin Press.

Fruh, E. G., Stewart, K. M., Lee, G. F. & Rohlich, G. A., 1966. Measurements of eutrophication and trends. *J. Wat. Pollut. Control Fed.* August: 1237-58

* Gerking, S. D., 1948. Destruction of submerged aquatic plants by 2, 4-D. *J. Wildl. Mgmt*, 12: 221-7.

Gilmour, A. J., 1965. The implications of industrial development on the ecology of a marine estuary. *Fish. Contr. Vict.* 20.

Goldman, C. R., Mason, D. T. & Hobbie, J. E., 1967. Two Antarctic desert lakes. *Limnol. Oceanogr.* 12: 295-310.

Hasler, A. D., 1947. Eutrophication of lakes by domestic drainage. *Ecology*, 28: 383-95.

Higginson, F. R., 1966. The distribution of submerged aquatic angiosperms in the Tuggerah Lakes system. *Proc. Linn. Soc. N.S.W.* 90: 328-34.

Holden, A. V., 1963. Agricultural chemicals and freshwater fisheries. *J. Effluent Wat. Treat.* December: 657-9.

Houghton, G. U., 1966. Maintaining the safety and quality of water supplies. In: R. H. Lowe-McConnell (Ed.), *Man-made Lakes*. London: Academic Press.

Ivlev, V. S., 1966. The biological productivity of waters. *J. Fish. Res. Bd Can.* 23: 1727-59 [translation by W. E. Ricker of paper which originally appeared in Russian in 1945].

Jones, J. R. E., 1964. *Fish and River Pollution*. London: Butterworths.

Kerekes, J. & Nursall, J. R., 1966. Eutrophication and senescence in a group of prairie-parkland lakes in Alberta, Canada. *Verh. int. Verein. theor. angew. Limnol.* 16: 65-73.

Lea, W. L., Rohlich, G. A. & Katz, W. J., 1954. Removal of phosphates from treated sewage. *Sewage ind. Wastes*, 26: 261-75.

† Ludwig, H. F., Kazmierczak, E. & Carter, R. C., 1964. Waste disposal and the future of Lake Tahoe. *J. sanit. Engng. Div. Am. Soc. Civ. Engrs.* 90: 27-51.

Lund, J. W. G., 1965. The ecology of the freshwater phytoplankton. *Biol. Rev.* 40: 231-93.

Mackenthun, K. M., 1965. *Nitrogen and Phosphorus in Water: an Annotated Selected Bibliography of their Biological Effects*. Washington, D.C.: U.S. Dept. Health, Education, and Welfare.

——— & Ingram, W. M., 1964. *Limnological Aspects of Recreational Lakes*. Washington: U.S. Public Health Service Publication No. 1167.

† Malhotra, S. K., Lee, G. F. & Rohlich, G. A., 1964. Nutrient removal from secondary effluent by alum flocculation and lime precipitation. *Int. J. Air Wat. Pollut.* 8: 487-500.

† McGauhey, P. H., Eliassen, R., Rohlich, G. A., Ludwig, H. F. & Pearson, E. A., 1963. *Comprehensive study on protection of water resources of Lake Tahoe basin through controlled waste disposal*. Prepared for Board of Directors, Lake Tahoe Area Council, Al Tahoe, California: 1-157.

† Neil, J. H., 1957. Problems and control of unnatural fertilization of lake waters. *Engng. Bull. Purdue Univ. Proc. XII Industrial Waste Conference*, 301-16.

Northcote, T. G. & Larkin, P. A., 1955. Indices of productivity in British Columbia lakes. *J. Fish. Res. Bd. Can.* 13: 515-40.

Oswald, W. J. & Golueke, C. G., 1966. Eutrophication trends in the United States—a problem? *J. Wat. Pollut. Control Fed.* June: 964-75.

† Owen, R., 1953. Removal of phosphorus from sewage plant effluent with lime. *Sewage ind. Wastes*, 25: 548-56.

Patten, B. C., 1956. Notes on the biology of *Myriophyllum spicatum* L. in a New Jersey lake. *Bull. Torrey bot. Club*, 83: 5-18.

PEARSALL, W. H., GARDINER, A. C. & GREENSHIELDS, F., 1946. Freshwater Biology and water supply in Britain. *Scient. Publs. Freshwat. biol. Ass.* 11.

PENNINGTON, W., 1943. Lake sediments: the bottom deposits of the north basin of Windermere, with special reference to the diatom succession. *New Phytol.* 42: 1-27.

PHILLIPSON, J., 1966. *Ecological Energetics.* London: Edward Arnold.

† PHINNEY, H. K. & PEEK, C. A., 1961. Klamath Lake, an instance of natural enrichment. In: *Algae and Metropolitan Wastes.* Cincinnati: Robert A. Taft Sanitary Engineering Center.

* *Rep. Freshwat. biol. Ass.* 5-14 (1937-46).

RUDD, R. L., 1964. *Pesticides and the Living Landscape.* Madison: University of Wisconsin Press.

RUTTNER, F., 1963. *Fundamentals of Limnology.* Toronto: University of Toronto Press. Third Edition.

SAWYER, C. N., 1947. Fertilization of lakes by agricultural and urban drainage. *J. New Engl. Wat. Wks. Ass.* 61: 109-27.

SAWYER, C. N., 1966. Basic concepts of eutrophication. *J. Wat. Pollut. Control Fed.* May: 737-44.

SPEIRS, J. M., 1948. Summary of literature on aquatic weed control. *Can. Fish Cult.* 3 (4): 20-32.

STEEMANN NIELSEN, E., 1955. The production of organic matter by the phytoplankton in a Danish lake receiving extraordinarily great amounts of nutrient salts. *Hydrobiologia,* 7: 68-74.

SURBER, E. W., 1949. Control of aquatic plants in ponds and lakes. *Fishery Leafl. Fish Wildl. Serv. U.S.* 344: 1-20.

* THOMAS, E. A., 1955. Phosphatgehalt der Gewässer und Gewässerschutz. *Mbull. schweiz. Ver. Gas-u. WassFachm.* 9/10: 1-16.

————, 1965. The eutrophication of lakes and rivers, cause and prevention. In: *Biological Problems in Water Pollution. Third Seminar, 1962. PHS Publ. No. 999-WP-25: 299-305.*

WEATHERLEY, A. & NICHOLLS, A. G., 1955. The effects of artificial enrichment of a lake. *Aust. J. mar. Freshwat. Res.* 6: 443-68.

WESTLAKE, D. F., 1960. Water weed and water management. *Instn. publ. Hlth. Engrs. J.* 59: 148-60.

WETZEL, R. G., 1963. Primary productivity of periphyton. *Nature,* 197: 1026-7.

————, 1964. A comparative study of the primary productivity of higher aquatic plants, periphyton, and phytoplankton in a large shallow lake. *Int. Revue ges. Hydrobiol. Hydrogr.* 49: 1-61.

WILLIAMS, W. D., 1967. The changing limnological scene in Victoria. In: A. Weatherley (Ed.), *Australian Inland Waters and Their Fauna: Eleven Studies.* Canberra: Australian National University Press.

————, 1968a. International symposium on eutrophication: some comments. *Aust. Soc. Limnol. Newsletter,* 6 (1): 18-20.

————, 1968b. *Australian Freshwater Life: the Invertebrates of Australian Inland Waters.* Melbourne: Sun Books.

WOOD, W. E., 1924. Increase of salt in soil and streams following the destruction of the natural vegetation. *J. Proc. R. Soc. West. Aust.* 10: 35-47.

* Not seen.

† Abstract in Mackenthun (1965) seen.

Description of Plate

PLATE 1

Two views of Lake Wendouree, Ballarat. Upper one shows large amounts of cut, submerged weed blown shorewards, a storm water drain, and fringing deciduous trees; lower one indicates the extent of emergent weed growth (June 1968).